N 70 34101

CASE FILE COPY

NASA TECHNICAL TRANSLATION NASA TT F-13,037

# FOUR UNRESOLVED PROBLEMS OF PLANETARY COSMOGONY

B. Yu. Levin

Translation of "Chetyre nereshennyye problemy planetnoy kosmogonii". Priroda, No. 6, 1969, pp. 22-34

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. 20546 JULY 1970

# FOUR UNRESOLVED PROBLEMS OF PLANETARY COSMOGONY

B. Yu. Levin[(1)]

ABSTRACT. The four unsolved problems are: the origin of the Earth's photoplanetary cloud, the condensation of matter in the cloud and fractionation of iron, the accumulation of the major planets and the differentiation of the Moon.

Some readers, glancing at the title of the present article, will immediately ask: just how many unresolved problems of planetary cosmogony are there and what problems have already been resolved? The number of unresolved problems is quite indeterminate -- it depends on how we classify the unresolved questions and which of them we raise to the rank of problems. The same situation applies to the resolved questions. Therefore, I shall limit myself to pointing out just one single resolved problem, namely -- the clarification of the question of the matter from which the planetary system was formed. It has now been firmly established that the planetary system was formed from a gas-dust cloud which existed at one time around the Sun. This makes it possible to avoid confusion and not examine all the possible formulations of the problems of planetary cosmogony. Rather, we can formulate a precise and clear research plan and know precisely which problems are fundamental and most important. /22*

In the present article, we shall examine the following four unresolved problems: the origin of the protoplanetary cloud; the condensation of matter in the cloud and the fractionation of iron; the accumulation of giant planets and, finally,

---

* Numbers in the margin indicate the pagination in the original foreign text.

(1) Dr. Phys-Math. Sciences

the differentiation of the Moon. The first two problems are the most important -- without solving them it is difficult to move ahead in any of the other fields of planetary cosmogony. The last two problems are more specific in nature, and are used to illustrate the great variety of questions which are encountered.

## FORMATION OF THE PLANETS FROM A GAS-DUST CLOUD

It is helpful to recall the basic hypotheses on which the modern ideas concerning the origin of the planets from the gas-dust cloud are based. First of all, there is an old argument, dating clear back to Kant and Laplace, and relating to the movement of all the planets along approximately circular orbits which lie in a single plane. Attempts to explain this in the time when Jean's theory was dominant by having the planetary orbits circularized by a resisting medium were not productive, since for bodies of planetary scale there is no resisting medium in the sense of aerodynamics and hydrodynamics, when the medium is purely resistive. Under astronomical conditions, the medium is at the same time a nutrient medium: for significant orbit circularization, the mass of the planet, or more precisely the mass of its nucleus, must increase several fold, i.e., there must actually be the formation of a planet from this medium.

Another hypothesis is the division of the planets into two groups: the small planets of the Earth type and the giants. It has long been known that blobs of incandescent solar matter, if they were torn from the Sun, should fly off into space. If we consider cold massive blobs, then in this case differentiation with respect to composition is impossible: selective elimination of only the light elements while retaining the heavier elements is not possible. On the Earth there is a deficit of the inert gases, amounting to about $10^3$ - $10^6$ /23
for xenon, the heaviest of the inert gases, in comparision with the cosmic abundance, and reaching $10^{10}$ - $10^{11}$ for the lighter elements such as neon. This indicates that the Earth was accumulated from solid bodies and gases did not participate in this formation. If there had initially been a blob of matter of solar composition, then the inert gases, and particularly heavy xenon, could not have been selectively scattered, particularly to such a degree.

On the other hand, the presence in the Earth and meteorites of such moderately volatile elements as cadmium, zinc, and mercury shows that the Earth and the parent bodies of the meteorites were formed from cold particles, since these elements would have been lost from hot particles. With regard to the meteorites, there are also many other arguments in favor of the hypothesis that they are the product of the accumulation of cold matter. Thus, all the data indicate that the planets were formed from a cold circumsolar gas-dust cloud.

## JOINT FORMATION OF THE SUN AND PROTOPLANETARY CLOUD

The surprising distribution of the angular momentum between the Sun and the planets (98% in the planets) led Shmidt to the supposition that the matter for the formation of the planets was captured by the Sun from interstellar matter. The possibility of such capture (by various mechanisms) has been repeatedly confirmed by numerous studies. However, the difficulty in explaining the fact that the Sun rotates in the same direction in which the planets revolve in their orbit around the Sun, with the axis of revolution nearly perpendicular to the planetary orbital plane, still remains unresolved. If we assume that this is the result of fallout of part of the cloud matter onto the Sun, then we find that prior to this fallout the Sun had practically no rotation. But this is difficult to reconcile with any hypothesis of the Sun's formation.

As long as 20 years ago many investigators indicated that the Sun and the protoplanetary cloud were formed jointly, in a single process. But at the same time the origin of the Sun itself remained so unclear that this hypothesis could not be concretized.

During the last decade, three hypotheses have appeared in which this joint formation is concretized in one way or another, and approaches are indicated which may lead to the solution of the problem of the distribution of the angular momentum between the Sun and the planets. Moreover, during this decade arguments have appeared which favor the theory that the protoplanetary cloud actually was formed together with the Sun. The first group of arguments relates to the field of nuclear physics.

Lithium, beryllium, and boron are present in the matter of the Earth and the meteorites. These elements are not formed in thermonuclear reactions in the interior of the stars; conversely these elements are consumed there and other ways must be found to explain their existence. Lithium has been detected in the atmospheres of stars of the T Tauri type and stars with magnetic activity. As early as the mid-fifties it was suggested that the formation of these elements is associated with the processes of electromagnetic acceleration of particles in atmospheres of such stars with splitting of the heavier nuclei by impacts of fast particles.

The first concretization of this idea was given in 1962 by Fowler, Greenstein, and Hoyle. They started from the fact that in addition to the very existence of Li, Be and B we must explain why the isotope ratio for Li and B differs quite markedly from unity. These authors believed that in the splitting process both isotopes should be formed in about equal quantities. However, the deficient Li and B isotopes have large cross sections for nuclear reactions with thermal neutrons. Therefore, the authors proposed the hypothesis in accordance with which the formation of Li, Be, B was shifted from the Sun itself into the icy planetisimals of approximately meteor dimensions, which were bombarded by energetic protons emitted by the youthful Sun.

In the course of the splitting process there appeared fast neutrons, which the authors believed were retarded and became thermal neutrons because of the presence of ice (i.e., hydrogen) in the planetesimals and then reacted with Li and B to create the isotope ratio which is observed. But it was found that these processes should have led to formation in the matter which was bombarded of a quantity of deuterium ($H^2$), which is an order of magnitude greater than that actually observed. Therefore, it was assumed that the planetisimals were quite large and only their outer layers were subjected to bombardment, and then the bombarded matter was mixed up with that which had not been bombarded. It was initially assumed that one tenth of the matter was bombarded, but later this figure was reduced to one twentieth.

However, this hypothesis ran into insuperable difficulties in explaining why in the Earth and the meteorites the elements which have a larger cross section with regard to neutrons (in certain cases this applies only to individual isotopes) are present in the same abundance and with the same isotopic composition. It was found that in the zone where the Earth was formed and in the zone where the meteorites were formed the bombardment was for some reason of the same intensity and all the other conditions which define the result of the bombardment also were the same. This led the authors themselves to question their hypothesis.

In general the data on the isotopic composition of gadolinium, europium, and samarium exclude the possibility of any processes with participation of the slow neutrons taking place in the protoplanetary cloud. The isotopes of Gd, Eu, and Sm, having tremendous slow neutron capture cross section, would /24
have to be present in sharply reduced quantities, which is not observed either in the Earth or meteorites[(1)].

A study by Bernas, Gradstein, Reeves, and Schatzman appeared in 1967, in which they returned to the original idea of the formation of Li, Be, and B in the stellar atmospheres. In this case the authors have in mind the outer layers of the protosun, where the temperature was 2 - 4 million degrees and where the formation of these elements took place more rapidly than their consumption. The authors relate the formation of Li, Be, B either to that time when our Sun was going through the last stage of contraction and was similar

---

(1) This question has been discussed previously in our journal (see Priroda, No. 11, 1963, p. 26). The previous article also presented some ideas on possible ways the light elements could have been formed. (ed).

to stars of the T Tauri type or even to the hypothetical prestellar stage, the so-called Herbig-Haro stage, when the stars still do not have any marked brilliance.

Formation of deuterium in the prestellar stage is not possible, and Schatzman suggested in 1967 that deuterium was formed somewhat later, not in the protosun atmosphere, but in the interior of the protoplanetary cloud as a result of splitting of the helium nuclei by solar protons. In order for such a process to occur, the interior of the cloud would have had to lose hydrogen for $10^5$ years until the intense corpuscular emission of the youthful Sun had terminated.

In order for all these processes to take place the planets would have had to have been formed not from matter captured from somewhere outside, but rather from matter which was separated from the protosun in the course of its contraction.

Another group of arguments in favor of joint formation of the Sun and the protoplanetary cloud relates to the thermal history of the parent bodies of the meteorites. These bodies undoubtedly passed through the high temperature stage and then cooled slowly. Widmanstatten figures were formed at temperatures of 450 - 700°C in the metallic phase of the meteorites. At this time the nickeliferous iron broke down into the $\alpha$- and $\gamma$-phases with different nickel content and the nickel diffused from one phase into the other. Several years ago Borovskii and Yavnel were the first to use x-ray spectral microanalysis to find the distribution profiles of nickel in taenite (the $\gamma$-phase, enriched with nickel). The diffusion took place under decreasing temperature conditions. The diffusion rate was reduced, and therefore, the edges of the taenite bars contain far more nickel than the central parts, to which the nickel was not able to diffuse (Figure 1). The steepness of the concentration reduction from the edge toward the center characterizes the rate of cooling in the temperature region of order 500°C.

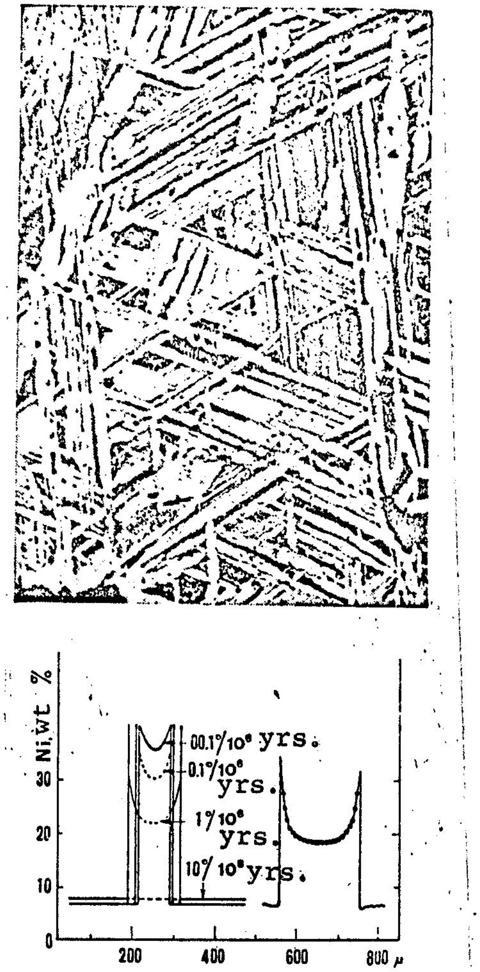

Figure 1. Widmanstatten figures on polished and etched surface of iron meteorite (above). Distribution of nickel in taenite (below): measured nickel distribution profile on the right, theoretical profiles calculated for different cooling rates on the left. Abscissa is the structure depth (in microns), ordinate is nickel content (in weight %).

Comparision of the theoretical nickel profiles calculated for different values of the cooling rate with the measured profiles makes it possible to determine the cooling rate of an iron meteorite with the Widmanstatten structure (Figure 1) or a meteorite with iron inclusions. It was found that the cooling of the majority of meteorites had taken place with a rate from a few tenths of a degree to 10 degrees per million years. Consequently, the cooling took place in the interiors of bodies of dimensions from a few tens to a few hundreds of kilometers. The steeper profiles which are sometimes encountered seem to indicate higher cooling rates and require bodies of dimensions of 10 km or less. However, such rates are fictitious and are associated with the separation of the nickeliferous iron into phases under supercooled conditions. Thus, the determination of the cooling rates of meteorites in the interiors of their parent bodies made it possible to estimate the dimensions of these bodies. For bodies of such dimensions there is no possibility of their heating by long-lived radio active elements.

The long-lived radioactive elements potassium, uranium and thorium are not capable of heating bodies of such small dimensions. As soon as the temperature increases by a few tens of degrees the heat loss begins to exceed the heat input. K, U, and Th can only heat bodies with diameters of 500 km or more (Figure 2).

Small bodies could be heated by $Al^{26}$ if it were present in sufficient /26 quantities, since its half-life is less than a million years. But, even with such rates of decomposition the heat release rate exceeds the rate of heat dissipation into space only in bodies of dimension greater than 50 km. Even $Al^{26}$ cannot heat bodies of smaller dimensions (Figure 3).

The question arises of where the $Al^{26}$ could come from. In galactic synthesis, judging by the neighboring stable isotopes, $Al^{26}$ is formed in a quantity such that no more than 4 - 5 million years should pass from the time of its formation to the formation of the parent bodies of the meteorites for it to be able to heat them. This time is very short and is in direct contradiction with the estimates of this same time interval made on the basis of the ratio of the original content of radioactive $J^{129}$ and its decomposition product -- excess $Xe^{129}$, and also on the basis of estimates of the original $Pu^{244}$ content and the product of its decomposition -- excess $Xe^{136}$. Estimates for these elements show that from 50 to 200 million years (depending on the assumptions with regard to the initial composition of the cosmic matter -- the content in this matter of $J^{129}$ and $Pu^{244}$) passed from the explosion of the supernova which gave birth to the $J^{129}$ and $Pu^{244}$ until the beginning of the accumulation of the products of their decomposition in the parent bodies of the meteorites. But, it was found that the same process which led to the deformation of Li, Be, and B also leads to the formation of $Al^{26}$. Moreover, if a very short time passed from the formation of the $Al^{26}$ to the formation of the parent bodies, then the amount of $Al^{26}$ would have been sufficient to heat the parent bodies of the meteorites to a temperature of about 1000°. We can assume that the heating actually amounted to about 500°C.

An interesting new possibility for heating the parent bodies of the meteorites has appeared recently. This is the hypothesis that the youthful

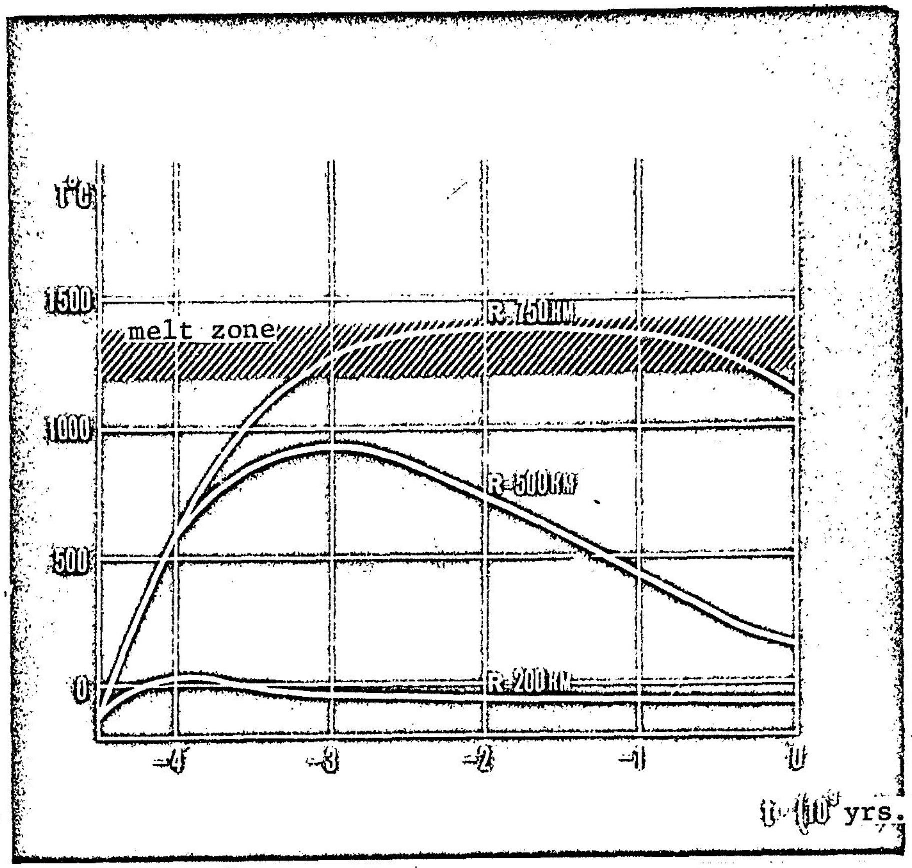


Figure 2. Time variation of temperature at the center of asteroids of different size R, heated by long-lived radioactive elements -- uranium, thorium, and potassium (calculation by S. V. Maeva)

Sun should have emitted a solar wind millions of times more intense than that emitted at the present time, which could possibly have carried away a mass amounting to half the present mass of the Sun. According to the calculations of the American scientists Sonnett, Colburn, and Schwartz, this solar wind was capable, if nonuniform, of creating inductive heating in the planetary bodies. According to their calculations the youthful Sun could have heated bodies of dimensions of hundreds of kilometers located in the asteroid zone to temperatures of the order of 1000°C or more.

However, the bodies themselves must have had a initial temperature of about 500°C in order to have adquate initial electrical conductivity. How can

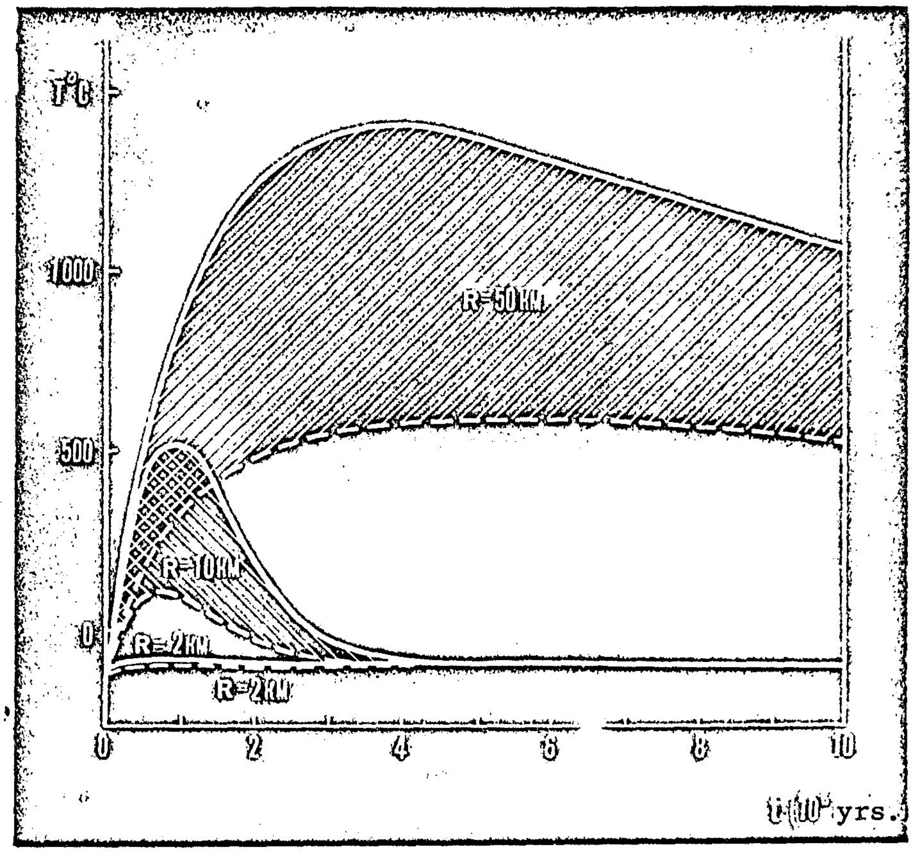


Figure 3. Time variation of temperature at the center of asteroids of different size, heated by short-lived isotope $Al^{26}$ (calculation by S. V. Mayeva). Shaded area corresponds to temperature range of possible $Al^{26}$ content.

such a temperature be attained? The authors consider their calculation shown in Table 1 as an example. If we take a somewhat higher electrical conductivity and assume a steeper temperature dependence of the conductivity, then this same heating could be obtained even with an initial temperature of 300°C. But even a temperature of 300°C is too high in the asteroid zone. Here $Al^{26}$ can be of help. It can heat the body to 300 - 500°C, and then the inductive heating mechanism takes over.

In either case, both the $Al^{26}$ heating mechanism and inductive heating require that the protoplanetary cloud and even the parent bodies of the meteorites be formed at the time when the Sun was still young, i.e., this must have

TABLE 1. EXAMPLE OF INDUCTIVE HEATING OF BODIES IN THE ASTEROID ZONE ($a$ = 2.5 A.U., $T = 2 \cdot 10^6$ yrs).

| Body radius (km) | initial temp. (°C) | | |
|---|---|---|---|
| | 300 | 400 | 500 |
| 1500 | | | 1063 |
| 1000 | 335 | 652 | 1181 |
| 500 | 332 | 577 | 1313 |
| 300 | 328 | 538 | 1265 |
| 150 | 323 | 498 | 1030 |
| 100 | 320 | | 920 |
| 75 | 319 | | 855 |
| 50 | 316 | | 770 |

been a process associated with the formation of the Sun itself.

Thus, there is some basis to believe that joint formation of the Sun and the protoplanetary cloud actually did take place.

THREE HYPOTHESES ON THE ORIGIN OF THE PROTOPLANETARY CLOUD

The first of the modern hypotheses was stated by Hoyle in Moscow at the International Astronomy Congress in 1958 and published in 1960. According to Hoyle's hypothesis, the rotating and contracting protosun became rotationally unstable when its radius dropped approximately to the radius of Mercury's orbit. Separation of matter from the Equator of the lenticular protosun took /27 place. As soon as the Sun (more precisely, the protosun), contracting still further, accelerated its rotation with relation to the separated matter, magnetic retardation of the Sun's rotation developed as a result of the fact that its magnetic field created coupling between the Sun and the separated matter.

The magnetic coupling retarding the rotation of the Sun first brought it out of the state of rotational instability, and thereby terminated further separation of matter and, second, transmitted angular momentum to the separated matter, forcing it to move away and propagate over the entire space of the present-day planetary system. Thus, according to Hoyle, there developed a protoplanetary cloud from which the planets were later formed (Figure 4).

We see in Figure 4, that the magnetic lines of force are twisted into spirals, and the Sun as it rotates pulls behind itself the separated matter thereby transmitting angular momentum to this matter. The difficulty is that for a reason which is not clear there must have been not only recession of

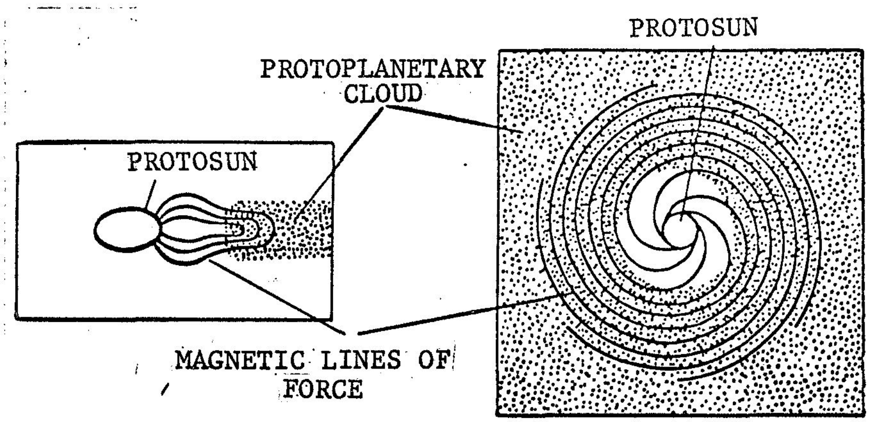


Figure 4. Scheme for transmission of angular momentum from protosun to separating matter as a result of magnetic coupling (Hoyle's hypothesis): section perpendicular to the protosun's Equator on the left, projection on the plane of the cloud on the right.

the ring of separated matter, but also its propagation over the entire space of the modern planetary system. Hoyle explains this by turbulent friction. But he knows that this analysis is not justified, since a scattered medium with Keplerian velocities of the rotational motion must be stable with regard to the onset of turbulence, and therefore must have laminar flow.

How could the separated matter have propagated over the entire space of the solar system? This appears to be the most unclear question in Hoyle's hypothesis.

A second hypothesis was proposed by the American astrophysicist Cameron, who did not agree with Hoyle's hypothesis on the basis that Hoyle chose a protosun having the required mass and the required angular momentum. Cameron chose a typical nebula with typical angular momentum. He examines a nebula with mass $2 - 4M_{\odot}$, which has a rotational velocity such that the separation of matter begins at a radius exceeding the radius of Pluto's orbit.

Moreover, Cameron considers that the protostar does not restructure itself or alter its internal structure in the course of the separation of the matter, rather there is simply a separation of the outer portions of the matter in /28
cylindrical layers. A quite surprising distribution of matter in the disk is obtained. Although the density of the matter increases toward the center, the shortening of the length of the circumference of the annular zones of the same width leads to a situation in which the larger portion of the mass is at the periphery of the disk. According to Cameron's scheme, inside the present-day orbit of the Earth the original mass must have been less than the mass of the Sun. There is practically no condensation in the center -- no Sun. All the matter has moved into the disk and only later, as a result of processes taking place in this disk, does part of the matter fall to the center, forming the Sun. The other, larger part was scattered into space. Only a very small fraction of the total mass of the matter was gathered into the planets. It is not at all clear how this process took place or just what defined that very small fraction of the mass which was gathered together into the planets. Moreover, in the Cameron hypothesis the Sun is formed after the protoplanetary cloud, and it is not at all clear where Li, Be, B,$H^2$ and A$^{26}$ came from to appear in the cloud and later form part of the composition of the planets.

Finally, the third hypothesis is that of Schatzman (1967) which was proposed in connection with his hypothesis on the formation of $H^2$ by splitting of He. In essence, the Schatzman hypothesis reactivates the Laplace hypothesis. It also has much in common with the Hoyle hypothesis. Here again there is /29
centrifugal separation of a small mass of the protoplanetary cloud; however,

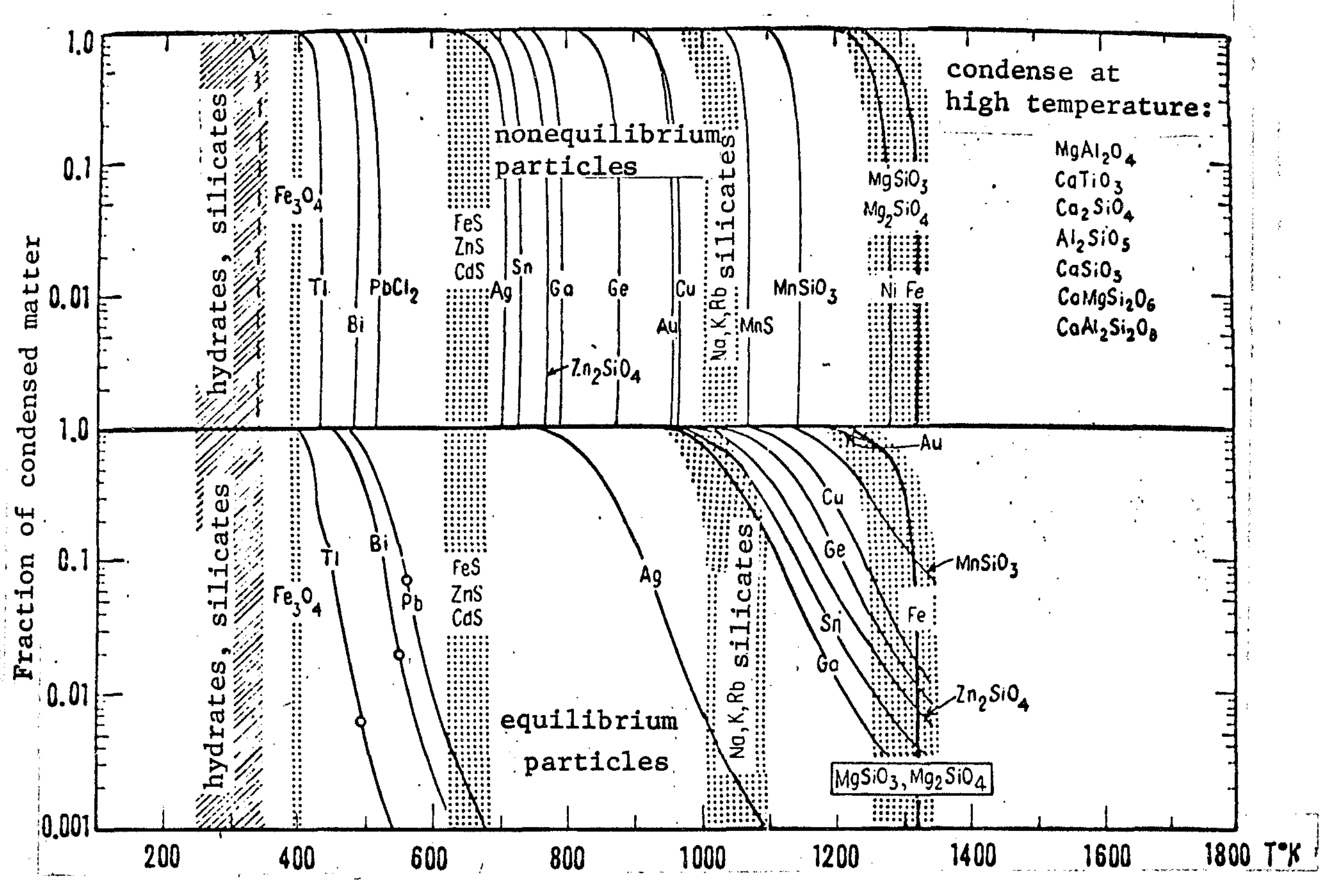


Figure 5. Condensation of various substances in the course of cooling of the protoplanetary cloud of solar composition

no magnetic coupling is assumed. The separation of matter begins in the region of the orbits of the most distant planets and continues in the course of the subsequent contraction of the protosun. The newly formed Sun has rapid rotation, which is then retarded as a result of powerful corpuscular emission, which carries away $10^{-4}$ - $10^{-5}$ of its mass.

## CONDENSATION IN THE CLOUD AND FRACTIONATION OF THE ELEMENTS

The three modern hypotheses on the origin of the protoplanetary cloud lead to very different pictures of its formation, with different distributions of the matter in the cloud and with a different cooling history. Without

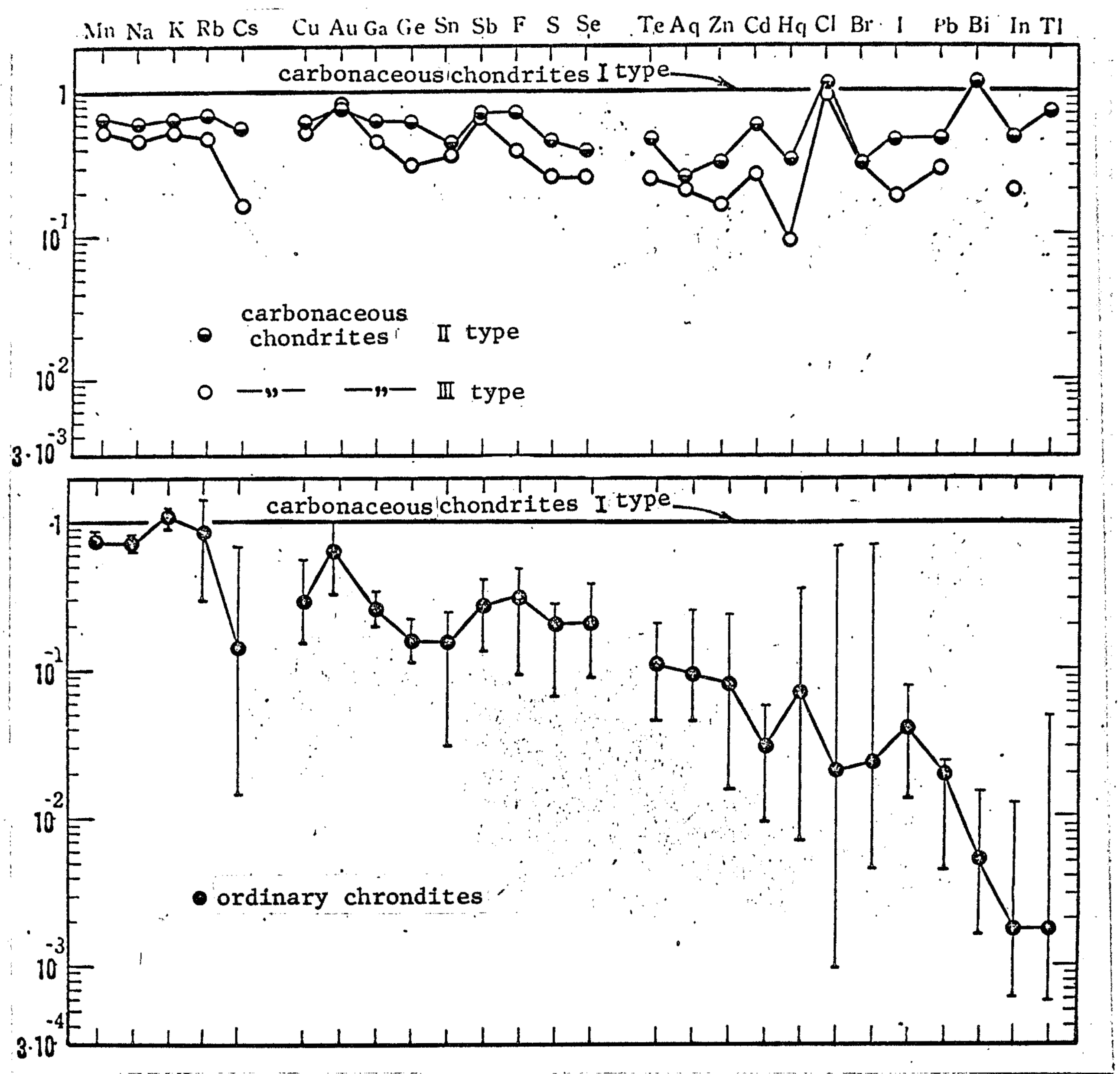


Figure 6. Deficit of moderately volatile elements in chondrites of various types with respect to carboniferous chondrites of type I.

making a choice among these hypotheses it is very difficult to study how the condensation of the dust particles took place in the cloud, which initially had a temperature of about 2000°C and was completely gaseous.

However, without studying the condensation process we cannot understand what determines the chemical composition of the Earth and the meteorites. We must begin the study of condensation in the protoplanetary cloud without having any firm concept of its formation.

Most of those investigating this process study equilibrium condensation, in which equilibrium between the dust particles and the gas is assumed. A study by Larimer also investigates condensation for the case in which the temperature drop was so rapid that the dust particles were stratified. Matter which condensed on the dust particle surface at a later time could not diffuse into the particle. Thus, there was equilibrium between the surface of the dust particles and the gas, while there was not equilibrium inside the dust particle.

However, the American physical chemists Blander and Katz (1967) insist that we must study nonequilibrium condensation, i.e., condensation from the supercooled gas, when there is no equilibrium betewen the solid particles and the gas and when particles with very marked differences in composition are formed. And, as a matter of fact, in the meteorites of the most primitive type which have not been subjected to further thermal metamorphism the individual mineral particles have very different composition: the minerals are not in thermodynamic equilibrium with one another.

According to Latimer the condensation proceeds as shown in Figure 5. A few, very nonvolatile substances condense at a temperature of about 1800 - 1900°C. Iron condenses at about 1600°C. Thanks to the presence of hydrogen, the iron separates in metallic form. The silicates solidify on cooling to 1400°C. At the time when the temperature reduces to these values about 90% of all the matter which is capable at all of becoming solid in the zone of planets of the Earth type condenses. Ferrous sulfide forms on cooling to 600° C as a result of the action of hydrogen sulfide on the metallic iron particles, and then below 400°C the iron rusts: water vapors lead to its oxidation.

To date no one has studied the effect of solar corpuscular radiation on the chemical processes in the cloud. There is only the rough estimate made by Donn. The energy radiated by the youthful Sun amounts to $10^{45}$ ergs. If all this energy were expended on chemical reactions $10^{55}$ molecules could be formed, i.e., the chemical transformations would take place in a mass of matter of the order of the Sun's mass. Thus, the chemical effect of this radiation on the protoplanetary cloud of far smaller mass could be quite significant.

To date the question has not been answered of the stage at which fractionation of the elements takes place. There are types of stony meteorites which contain elements in the quantities corresponding to their chemical abundance, while in meteorites of other types some deficit of these elements is observed (Figure 6).

The carboniferous chondrites of type I contain all the elements in their cosmic abundance. The meteorites of this type are formed of fine-grained matter consisting of hydrated silicates. They have no metallic iron (all the iron is oxidized) and there are various organic compounds. The carboniferous chondrites of types II and III also contain minerals such as olivine, pyroxene, and some metallic iron.

If we take the content of the elements in the carboniferous chondrites of type I as unity, then the deficiency of about 30 moderately volatile elements in the carboniferous chondrites of types II and III and in the ordinary chondrites is as shown in Figure 6. According to Anders, a well known meteorite expert, the curves for the carboniferous chondrites of types II and III give a basis to believe that elements of different volatility are lost to the same degree. On this basis he concludes that the carboniferous chondrites of types II and III are a mixture of type I chondrite matter with some other substance -- a higher temperature fraction containing metallic iron, olivine, and pyroxene. In the ordinary chondrites, consisting basically of olivine and pyroxene and containing a large number of metallic inclusions the deficit of these elements is much higher. But then, we can not draw a horizontal straight line through the points and consider that all the elements are lost to the same degree, and therefore, the two-component Anders scheme is applicable to the ordinary chondrites only with a large number of artifical assumptions.

The Australian geophysicist Ringwood suggests that the deficit appeared not at the time of condensation, but in the interiors of the parent bodies of the meteorites.

It is very important that in addition to the difference in the content /30 of the moderately volatile elements there is a large difference in the iron content in the different groups of meteorites. In Figure 7, the iron oxide content is plotted along the abscissa,and the metallic and sulfide iron content is plotted along the ordinate. If the overall iron content were the same and the only question was the relative amount of reduced and oxidized iron, the points would lie along a straight line with a slope of 45°. In actuality, we encounter groups of chondrites which contain an obviously different amount of iron. Unfortunately, we do not know how this separation took place.

The question of the iron in meteorites also has other aspects. There is about 25% iron in the meteorites, or several times more than in the solar photosphere. With regard to the nonvolatile elements, which make up the larger portion of the meteorites, they amount to only about 6% of the photosphere--why we do not know.

The iron content in the solar corona is greater than in the photosphere, and Cameron considers that the metals, including iron, are carried out into the corona by selective light pressure and are lost together with the solar wind. As a result the solar photosphere is deficient in the metals and iron, while the meteorites show the correct cosmic abundance of iron.

Urey and Arnold argue against this idea. They believe that the solar wind carries away the chemical elements in the normal solar proportions and assume

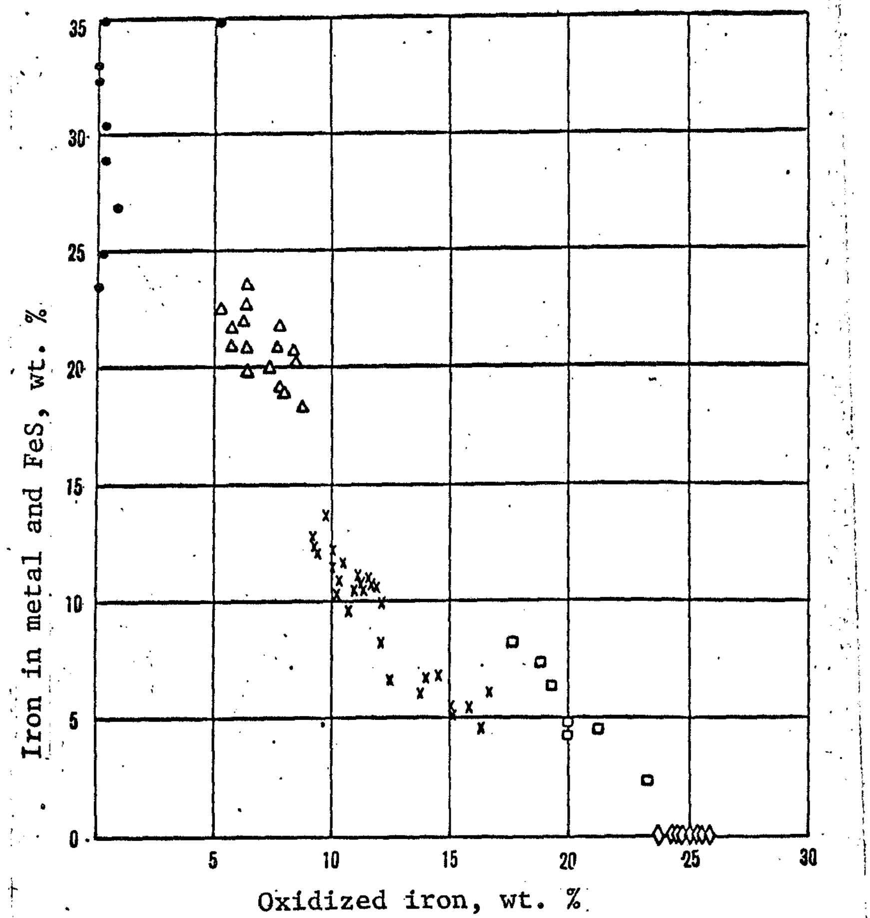


Figure 7. Relationship between content of oxidized iron and iron in metal and sulfide forms in chondrites, indicating the separation into individual groups and variations within the groups (Mason, 1962).

● – enstatite chondrites
△ – olivine-bronzitite chondrites
× – olivine-hypersthene chondrites
□ – olivine-pigeonite chondrites
◇ – carboniferous chondrites

that the solar corona is enriched with iron as a result of the fact that matter of meteoritic type, the matter of the zodiacal light, is being scattered into the corona all the time. In the corona this matter is vaporized, the result being iron enrichment.

Still more complex is the question of the iron content in the planets of the Earth group. Estimates of the iron fraction in the Earth and Venus depend significantly on whether or not the old hypothesis of the "iron" core of the Earth[(2)] is adopted of the Lodochnikov-Ramsey hypothesis on a core made up of metallized silicates. If we use the "iron" Earth core hypothesis, we find that even if we exclude Mercury we have a difference of at least a factor of six in the content of the iron-nickel-silicon alloy and a difference of a factor of 1.5 in the overal iron content as an element (see columns 1 and 2 of Table 2).

TABLE 2. IRON CONTENT IN PLANETS OF THE EARTH GROUP (in mass %)

| Planet | Data based on the hypothesis of the "iron" Earth core | | Data based on the hypothesis of the Earth's core consisting of metallized silicates | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Mercury | 63 | 57 | 60 | 55 |
| Venus | 26 | 39 | 0-25 | 27-40 |
| Earth | 31.5 | 42 | 0-2 | 25-27 |
| Moon | 5 | 28 | 0 | 25 |
| Mars | 19 | 35 | 0-5 | 30 |

NOTE: 1) Content of Fe, Ni, Si. 2) Same data, converted approximately to the overall iron content under the assumption that the iron content in the silicates is 25%. 3) Metallic nickeliferous iron content. 4) Same data converted approximately to the overall iron content under the assumption that its content in the silicates is 25%.

(2) After the experiments on impact contraction of iron and nickeliferous iron, made by Al'tshuler et. al., (UFN [Advances in the Physical Sciences], Vol. 85, No. 2, 1965, p. 197), the adherents of the hypothesis on the "iron" core of the Earth no longer believe that this core consists of nickeliferous iron, rather they assume some admixture of silicon, which reduces the density of this alloy and brings this value into agreement with the geophysical data.

However, if we use the assumption that the Earth's core consists of metallized silicates we can obtain a more encouraging picture. Models with a very different amount of metallic nickeliferous iron and, correspondingly, with different content of iron as an element, are admissible for Venus. But, if we take for Venus models without a significant iron core, then we find that Venus, the Earth, Moon, and Mars can have similar composition, differing only slightly (as for the meteorites) with regard to the iron content.

While we can bring the data for Venus, Earth, Moon, and Mars into agreement, nothing can be done with Mercury, whose high density indicates that it contains about 60% nickeliferous iron, i.e., 50 - 55% of the iron as an element. This is not similar to any of the other planets. It appears that the /32 temperature of the dust matter in the zone where Mercury was formed did not descend to 400°C; therefore the iron remained in the metallic state and its magnetic properties showed up in preferential accumulation of the iron dust particles.

## PROBLEMS OF THE ACCUMULATION OF THE GIANTS

The planets of the terrestrial group are small and they cannot throw matter from the zone of its formation by their own perturbations. Practically all the solid matter which existed in the formation zone of the planets of the Earth group entered into the composition of these planets. In the giants the picture is different. Their masses are so large that they could by their own perturbation throw some amount of matter beyond the limits of the planetary system.

If we assume that in the zone of Uranus and Neptune there was only that matter which today makes up the composition of these planets, then a time exceeding the age of the solar system would have been required for the accumulation of Uranus and Neptune. Only by assuming that initially there was considerably more matter in that zone can we obtain an acceptable duration

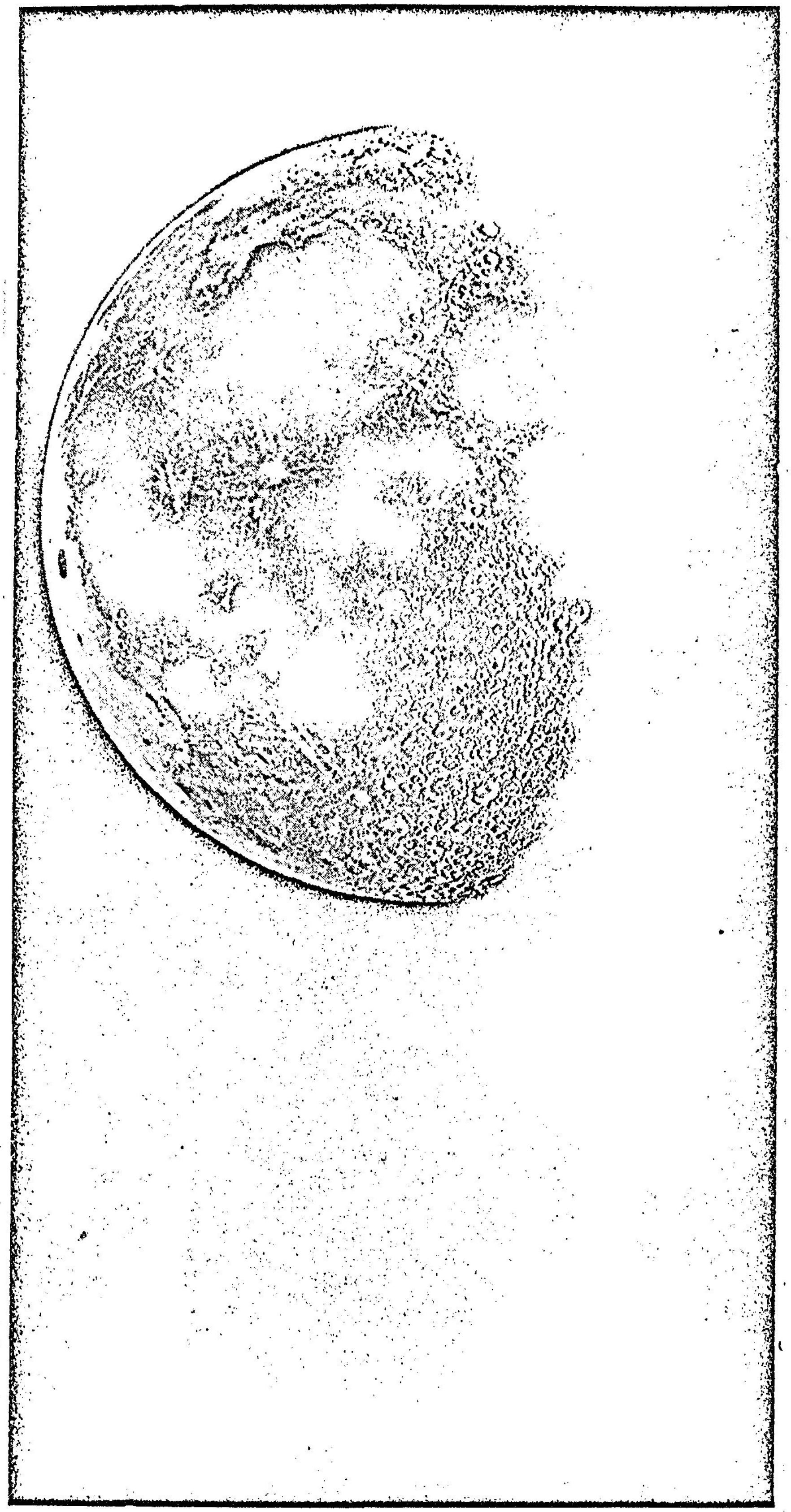

Figure 8. Photograph of Moon showing existence of continents and maria regions on the lunar surface.

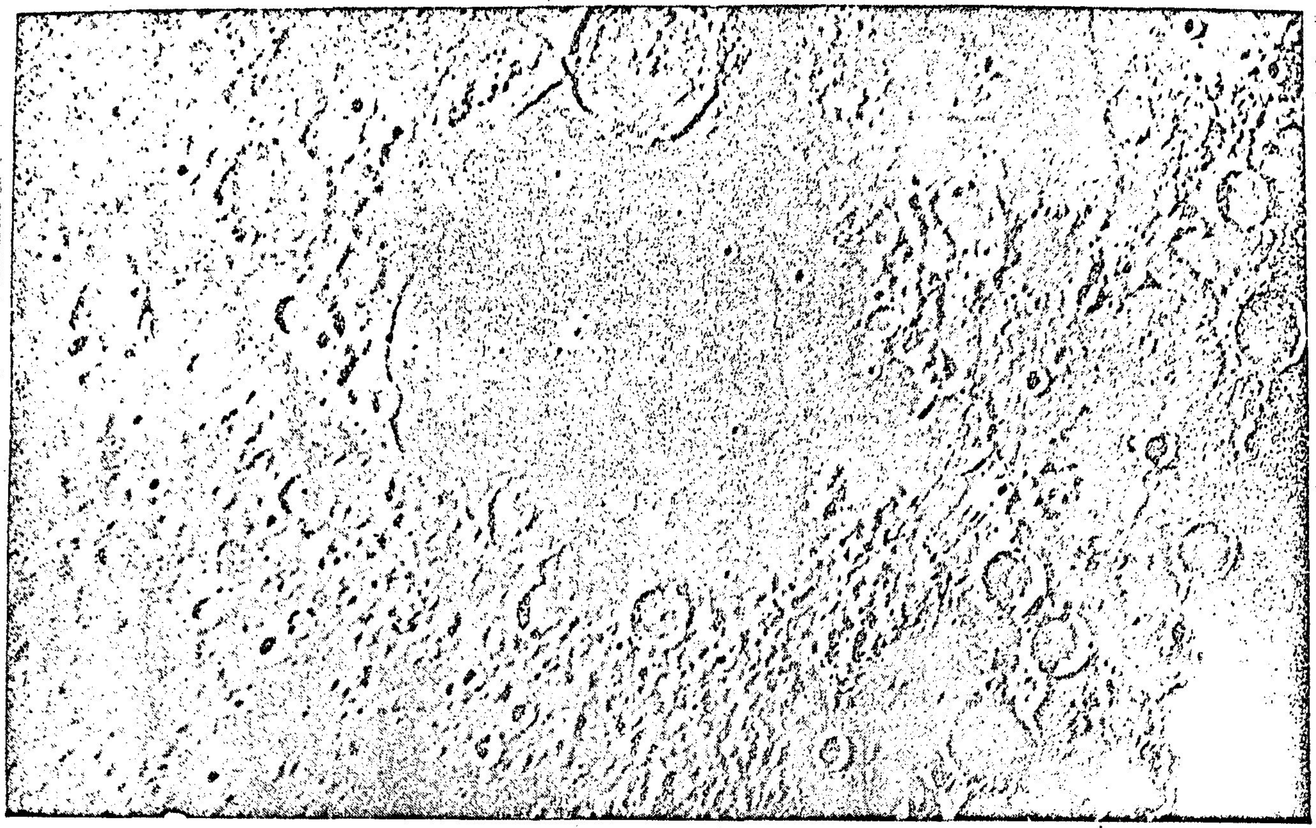

Figure 9. Circular Sea of Moisture. On its surface, as on the surface of the other maria, there are very few craters.

of the accumulation time. In the giants zone the solid bodies had an ice composition, and the ejection of bodies from this zone was at the same time the process of the formation of the cloud of cometary nuclei which at the present time surrounds the solar system. It extends to a distance of 100,000 to 150,000 A.U. and serves as a source for the comets which are observed today.

Thus, even in the framework of the purely mechanical formulation of the question of the accumulation of the planets from solid matter, the process of the formation of the giants is considerably more complex than the process of the accumulation of the planets of the Earth group.

However, Jupiter and Saturn contain a tremendous amount of hydrogen. In order for the hydrogen to freeze and appear in the composition of the planets in the solid state it is necessary to reduce the temperature of the outer parts of the protoplanetary cloud to 4 - 5°K. This seemed like a possibility, since the outer part of the cloud was shielded from the solar rays by the inner part. However, in recent years it has been found that there is helium in the atmosphere of Jupiter, which could not in any way get into the solid state in the protoplanetary cloud. Thus, Jupiter and Saturn were accumulated from both solid and gaseous matter. Unfortunately, it is not entirely clear at what stage of the accumulation of the solid matter the planet transitions to the regime in which it is capable of beginning to absorb gaseous matter into itself as well.

It is quite possible that the mass at which the accumulation of gases begins is less than the mass of the Earth. If this is confirmed, then in order to explain why the Earth does not have its primeval atmosphere it will be necessary to assume that by the end of the accumulation of the Earth the gas had already dissipated from the Earth's "feeding zone."

## DIFFERENTIATION OF THE MOON

It is well known that on the Moon there are lighter regions which are densely strewn with craters and darker lowlands on which there are considerably fewer craters (Figure 8). The lowlands have been termed seas and the light regions are termed continents. Most of the Moon researchers have long assumed that the seas were formed by effusive lava, although there has been no real proof of this and therefore, we cannot categorically reject the hypothesis of Gold, who considered that the seas were depressions filled with fine dust.

The number of craters on the seas corresponds well with expectations based on estimates of the frequency of impacts on the surface of the Moon of small asteroids and cometary nuclei which fly into the region of the Earth's orbit. The observed craters could have been formed during the time of the existence of the seas, amounting to 2 - 3 billion years.

But, on the continents there are so many craters that they could not have been formed during the entire time of existence of the Moon with this same crater formation rate (Figure 9). After all, the age of the Moon and the age of the entire solar system does not exceed five billion years, i.e., this age is only twice that of the lunar seas. Therefore, many Moon researchers, particularly the adherents of the impact origin of the craters, considered the continents to be remnants of the primeval outer layer of the Moon, strewn with craters in the final stage of its accumulation. According to the estimate of the American investigator Marcus, the density of the craters on the continents corresponds to saturation and cannot be increased by further bombardment: the number of craters destroyed in this process would equal the number of newly formed craters.

However, along with these viewpoints there have also been the assumptions that the lunar continents, like those on the Earth, consist of granite rocks. There has been more unity of the views with regard to the composition of the seas: nearly all the investigators have considered that they are composed of basaltic lava, since this lava is far less viscous than granite lava and therefore could spread out over tremendous areas.

Direct measurements of the composition of the lunar surface layer, first made by Academicians Vinogradov and Surkov with the aid of the Soviet automatic stations Luna-10 and Luna-12, provided remarkable confirmation of the hypotheses on the basaltic composition of the lunar continents. The latter composition was in agreement with the hypothesis that the continents are made up of primeval granular matter which has not been replaced by lava pouring out of the interior of the Moon.

Theoretical calculations of the thermal history of the Moon, made by /34
Maeva under the direction of the present author, have shown that heating by radioactive elements could have caused melting of a considerable portion of the lunar interior (Figure 10). Formation and upwelling of the lava 2 - 3 billion

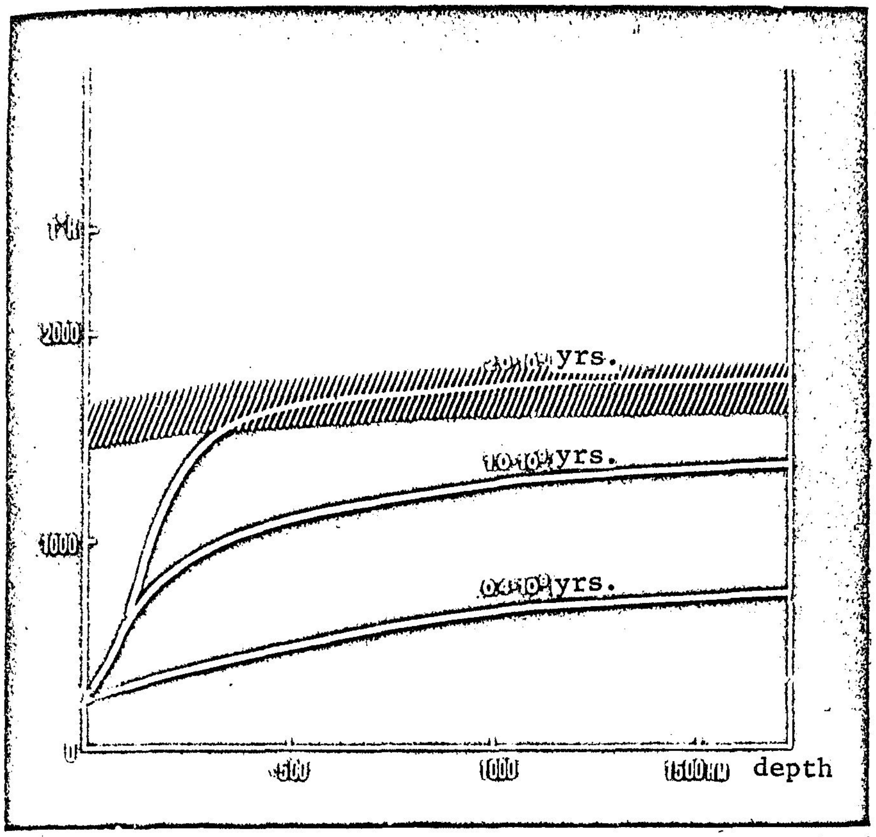


Figure 10. Heating of the Moon by long-lived radioactive elements (U, Th, k). Region of melting temperatures is shaded. Melting occurred two million years after the formation of the Moon, accompanied by differentiation of the matter in the interior of the Moon and emergence of the larger portion of the radioactive elements to the surface (calculation by S. V. Mayeva).

years ago created conditions favorable for outpouring of the lava. However, judging by the structure of the lunar surface the outpouring of the lava did not, as a rule, take place spontaneously, but rather as a result of impacts of large bodies, which led to sinking of the surrounding regions and the formation of circular maria. The rare spontaneous outpouring of lava or its spreading beyond the limits of the circular maria led to the formation of maria of irregular form. Since basaltic lava is markedly enriched with radioactive elements, upwelling of this lava and breakthrough to the surface facilitated the escape into space of the heat released by the radioactive elements. This led to transition of the Moon from heating to cooling (Figure 11),

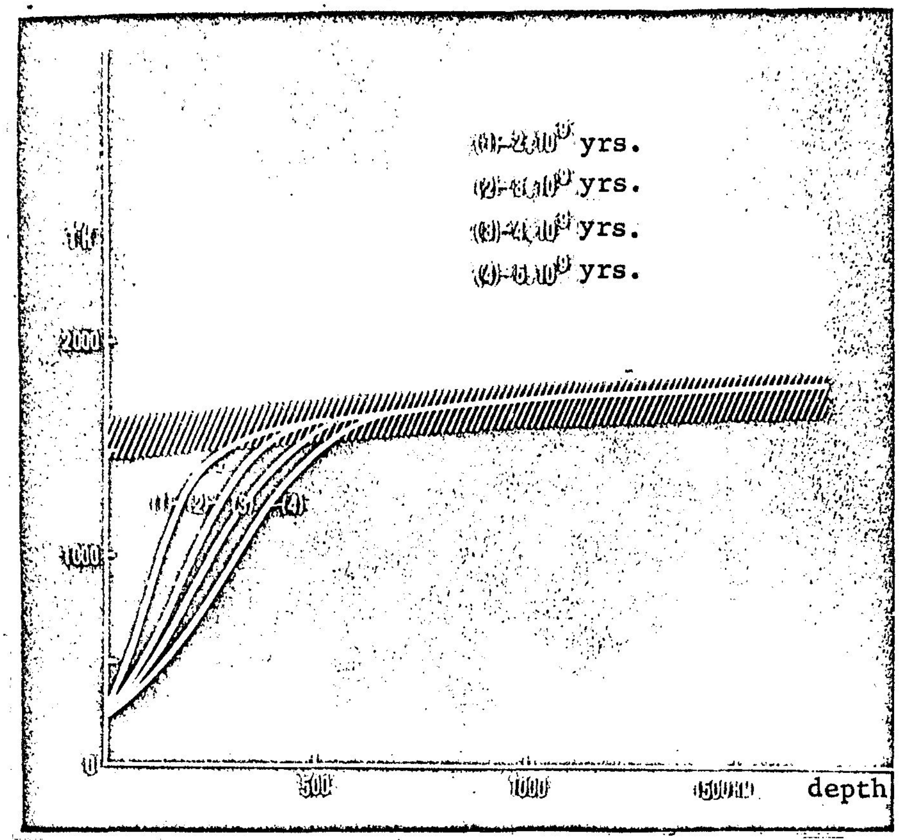


Figure 11. Cooling of the Moon. Emergence of radioactive elements to the surface facilitated diffusion into space of the heat released by the elements and transition of the Moon from heating to cooling (calculation by S. V. Mayeva).

which occurred 2 - 3 billion years ago. The previous favorable conditions for lava outpouring do not now exist on the Moon.

At first glance everything seems to be quite clear and there is no basis for listing the problem of lunar differentiation among the number of unresolved problems. Unfortunately, there is a basis for doing so.

First of all, it is still not clear why the lava outpourings do not cover the entire lunar surface, why there are still regions in the form of continents which are remnants of the primeval outer layer. The solid silicates are more dense than molten silicates of the same composition, and the partial retention of the primeval outer layer indicates some as yet not very clear peculiarities of the lunar outer layer composition and structure, which have made the primeval layer lighter in weight than the basaltic magmas which have risen from below.

Secondly, radio astonomical measurements of the temperature of the lunar surface layer, made by Troitskiy and his co-workers, have led to the conclusion that there is a large heat flux from the interior of the Moon -- so large that even at the present time incandescent matter may be located at very shallow depths. But, this is not compatible with the deviations of the lunar figure from hydrostatic equilibrium.

On the other hand, observations of the magnetic fields in the vicinity of the Moon made by American investigators (Ness et. al.) led them to precisely the opposite conclusion, that the interior of the Moon must have low electrical conductivity and, therefore, must be relatively cold. So cold that it is not clear how to explain the differentiation of the lunar interior, which shows up in the existence of the basaltic maria.

It is these contraditions which form the basis for including the problem of lunar differentiation among the list of unresolved problems.

I would like to conclude with the point with which I started: the clarification of the nature of the matter from which our planetary system was formed, the clarification of the basic features of the process of the planetary system formation, provides a basis for a very optimistic evaluation of the future development of planetary cosmogony. The combination of theoretical investigations, observations from the Earth, and cosmic experiments is leading to a situation in which those problems which at the present time must be considered unresolved will one by one move over into the category of resolved problems.

UDC 523.40

Translated for National Aeronautics and Space Administration under Contract No. NASw 2035, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93103